Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Improving Palm Oil Methylester Using Catalytic Cracking Methode

Nurkholis Hamidi[1,*], Rony Sessar Anugrah[1], Winarto[1], Lilis Yuliati[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, Brawijaya University, Malang, Indonesia

ABSTRACT

Biodiesel is a prospective substitute for diesel fuel that has garnered attention in recent years due to its environmentally conscious properties. However, biodiesel still exhibits several drawbacks in its features, namely in terms of its high viscosity, density, and flashpoint values. These factors can significantly impact the operation of the fuel motor engine, preventing it from operating at its ideal level. Consequently, biodiesel requires further processing to acquire properties that are appropriate for use in combustion engines, such as catalytic cracking with heterogeneous catalysts. The use of heterogeneous (solid) catalysts can effectively overcome this shortcoming. This study involved conducting experimental research on the effect of catalytic cracking on the characteristics of methyl-ester oil using a natural zeolite. The methyl ester was mixed with 5%mass of zeolite and heated for durations of 10, 15, 20, 25, and 30 minutes. Heterogeneous catalysts offer several benefits, such as facilitating the separation of biodiesel products, as well as the ability to regenerate and reuse the catalyst. To enhance the cost-effectiveness of biodiesel manufacturing. This study observed alterations in both the chemical composition and physical properties, as demonstrated by FTIR analysis and fuel physical properties tests. The content is primarily composed of double-chain (C=O) and single-chain (OH, C-CH3, CH2, CH3, C-O, C-CL, and C-Br) functional groups detected at absorption wavelengths ranging from 586.17 to 3006.45 cm^{-1}. The viscosity, density, flashpoint, and calorific value of the methyl-ester with 5% zeolite combination dropped as the heating time increased. This is due to the elongation and subsequent dissociation of the hydrocarbon chains comprising the methyl-ester, which previously exhibited attractive forces. As a result, the intermolecular forces diminish, leading to a drop in the value of physical qualities.

Keywords:
Catalytic cracking; natural zeolite; methyl ester; FTIR; fuel properties

1. Introduction

The accelerating rate of population growth and industrialization necessitates a corresponding increase in energy demand. At present, fossil fuels including petroleum, natural gas, and coal are the primary energy sources used for industrial, transportation, and domestic purposes. The extensive exploitation of fossil fuels leads to the depletion of the natural reserves of fossil energy, as energy from fossil fuels is non-renewable. Given the annual growth in energy demands, it is imperative to develop renewable energy solutions capable of satisfying future energy requirements. To address

* *Corresponding author.*
E-mail address: hamidy@ub.ac.id

https://doi.org/10.37934/araset.64.2.7280

this issue, some researchers recommend to use biomass and biofuel for substitute the fossil fuel [1-3]. Numerous nations also have implemented rules that promote the use of biodiesel fuel (BDF), which is produced from vegetable and animal oils, in place of diesel fuel for industry and transportation. Utilizing renewable biodiesel has the dual purpose of addressing energy scarcity and mitigating environmental deterioration caused by extensive reliance on fossil fuels.

Vegetable oil such as palm oil can be used as an alternative fuel in diesel engines due to its composition and features that are compatible with diesel fuel. Palm oil has a hydrocarbon chain that closely resembles that of fossil oil. Nevertheless, the utilization of palm oil as a fuel for engines encounters challenges, including its elevated viscosity, density, and flashpoint in comparison to fossil diesel oil. Highly viscous and dense fuel in a combustion engine can lead to a loss in engine performance. According to Rodrigues *et al.*, [4], when the fuel viscosity is high, it might lead to a decrease in atomization power, resulting in a loss in engine power. Increased viscosity can impede the functioning of the injection pump in a diesel engine, preventing effective atomization when biodiesel is sprayed into the combustion chamber. The engine necessitates a greater amount of energy to atomize the combustion chamber. As a result, the injection produces fuel droplets that are challenging to burn, rather than a volatile mist [5,6]. The high flashpoint is also a disadvantage of applying vegetable oil. The flashpoint of a fuel is the lowest temperature at which the fuel can produce a vapor-air mixture that is capable of igniting or burning. A fuel with a higher flashpoint value will have a longer igniting time and may decrease the efficiency of the combustion engine [7,8]. Hence, it is necessary to refine palm oil into a more refined oil to utilize it as a replacement for traditional oil.

Methyl ester biodiesel is often produced by the transesterification process, which involves reacting vegetable and animal oils with alcohol [9-11]. Methyl ester is a viable alternative fuel that may be derived from vegetable oil and possesses the same physical and chemical characteristics as petroleum. Unfortunately, there are several drawbacks to using biodiesel derived from transesterification as opposed to conventional fuels. These include corrosion caused by the high unsaturated content, poor storage stability, inadequacy in cold climates, low energy content, toxic methane content, and high cost. The cost of bio-based fuels, like methyl esters, is higher in comparison to petroleum due to their susceptibility to fluctuations in raw material prices. Specifically, around 60–70% of the price of methyl ester is contingent upon the price of vegetable oil. It also has shortcomings related to its physical properties, so some researchers suggest mixing it with kerosene, diesel, or additives to improve it [12,13]. Hence, it is necessary to employ supplementary techniques to enhance the efficiency of methyl-ester usage. Catalytic cracking technology is one method that can be applied to improve the properties of biodiesel.

Catalytic cracking is a reaction that uses a catalyst (a heterogeneous catalyst) as a material that can accelerate the reaction rate and reach equilibrium, the end product of the reaction, through the mechanism of carbonium ion formation [14]. Catalytic cracking is a common way to break long carbon chains into shorter hydrocarbon chains using a catalyst. Several studies have indicated that the process of catalytic cracking enhances the competitiveness of biodiesel [15-19]. With the aid of a catalyst, lengthy carbon chains are split into short, simple hydrocarbon chains or molecules during catalytic cracking [20-23]. In addition, this process can be carried out at lower temperatures and pressures with the help of a catalyst.

Precipitation deposition, ion exchange, adsorption, and impregnation are several ways employed to utilize catalysts in inducing cracking. Immersing the catalyst carrier in a solution containing the active metal and precursor salt infuses it [24,25]. When there is no exchange of anions or cations with the active phase, impregnation occurs. Ion exchange involves the interchange of ions between the active metal and the carrier, as opposed to impregnation. This method uses precursor salts to

add cations to the zeolite through alkali or alkaline earth cation exchange [26-28]. Diverse catalysts used in certain experiments yielded distinct biofuels when used to crack various vegetable oils. Factors like reaction time, reaction temperature, and catalyst type can influence the composition of the produced biofuel. This procedure has been employed to transform vegetable oils into low-molecular-weight hydrocarbon fractions to resolve biodiesel issues associated with fuel characteristics.

Researchers are currently developing a cracking process using readily available natural zeolite catalysts to manufacture biofuel from palm oil. This process can break down complex hydrocarbons into simpler molecules, thereby increasing the quality and quantity of the products produced. This study aims to examine the feasibility of the proposed methods (catalytic cracking using natural zeolite) for improving biodiesel quality, and some fuel properties of the palm oil methyl esters have been analyzed.

2. Methodology

2.1 Material

This research used an esterification process to prepare biodiesel (methyl ester) from palm oil. We then cracked the methyl ester using the proposed method. We use natural zeolite as a catalyst for the catalytic cracking process. Zeolite catalysts are physically and chemically activated. Physical activation consists of heating the zeolite to evaporate the water trapped in the pores of the zeolite crystals so that the surface area is large. We carry out chemical activation to remove any remaining dirt from the zeolite surface. Zeolite activation begins with washing with distilled water. We then dried it at 110 °C. Following the washing and drying process, we soaked the zeolite in 2 M HCl and then baked it at 500 °C for 3 hours.

2.2 Experimental Procedure

Figure 1 show the schematic of apparatus instalation for cracking process. We carry out the biodiesel cracking process by mixing zeolite with 5% of the mass. The mass of the biodiesel sample for each test is 300 grams. Next, we carry out the cracking process by heating the catalyst and biodiesel mixture to a temperature of 100 °C. We varied the heating time for 10, 15, 20, 25, and 30 minutes. We test several biodiesel properties, including viscosity, density, flash point, and heating value, after the cracking process. We also conducted FTIR testing on the biodiesel cracking results in this study. We used FTIR to look at how changing the age of transformer oil insulation affected the chemical bonds in the sample's functional group composition [29].

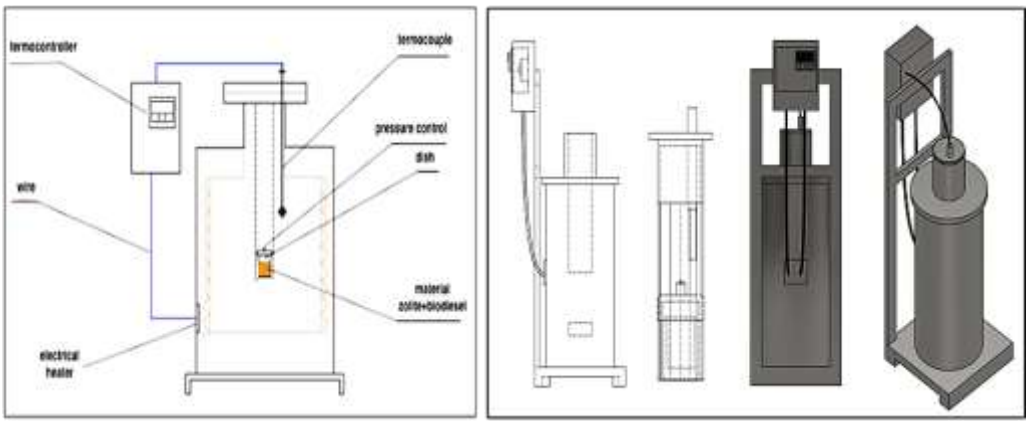

Fig. 1. Schematic of the apparatus for the cracking process

3. Results and Discussion

3.1 FTIR (Fourier-Transform Infrared Spectroscopy) Analysis

FTIR (Fourier-Transform Infrared Spectroscopy) analysis was conducted to identify compounds in the biodiesel. Biodiesel methyl esters were analysed by FTIR after the cracking process. FTIR analysis have been carried out on all samples. The wave absorption from FTIR test results can be seen in Figure 2 and Table 1. The tested samples exhibit wave absorption in the range of 1000–1300 cm^{-1} and 1741.40 cm^{-1}, indicating the presence of C–OO and C=O functional groups.

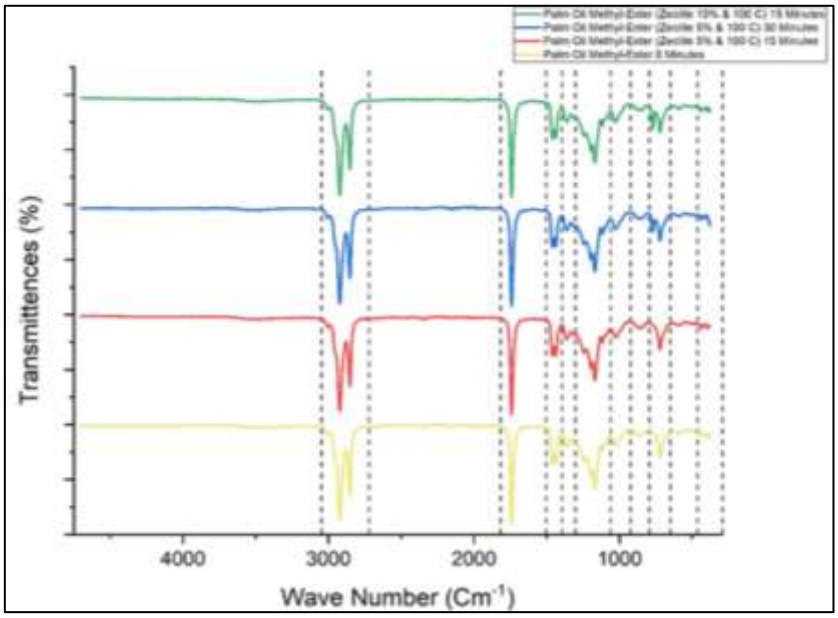

Fig. 2. FTIR spectra wave results

Table 1
The functional group contained in the methyl-ester oil in each wavenumber

Vibration type	Wave number (cm^{-1})				
	Palm oil methyl-ester	Palm oil methyl-ester (zeolite 5% & 100 °C) in 15 minutes	Palm oil methyl-ester (zeolite 5% & 100 °C) in 30 minutes	Palm oil methyl-ester (zeolite 5% & 100 °C) in 15 minutes	Intensity
O-H	3005.03	3006.45	3006.45	3006.45	Medium to strong
C-CH_3 (stretching)	2922-2853.85	2922.31-2853.85	2922.31-2853.85	2922.31-2853.85	Strong
C=O	1741.40	1741.40	1741.40	1741.40	Medium to strong
CH_2 bending (C-C)	1437.62-1461.87	1437.62-1461.87	1437.62-1461.87	1437.62-1461.87	Week to strong
CH_3 bending (C-C)	1362.03	1360.61	1360.61	1362.61	Medium
C-O	1118.15-1243.66	1118.15-1243.66	1118.15-1243.66	1118.15-1243.66	Strong
C-C	1021.17	1029.72	1031.15	1031.15	Medium to strong
C-C (C out plane)	848.69	850.02	847.02	848.60	Low to medium
C-CL	-	-	722.66-771.A58	721.66-771.58	Strong
C-Br	-	-	-	586.17	Strong

Subsequently, the oxygen content that binds to other chemical elements can form different compounds beyond the methyl ester. The oxygen content in the mixture can take several forms, including alcohols, ethers, carboxylic acids, ketone groups, and esters. Furthermore, we analysed the spectra and transmittance data for each sample in Figure 3 (subtopic 3.2) to determine the dominance of the contents, specifically by focusing on the transmittance peaks of the functional groups detected in each wave. The results are as shown in Table 2.

Table 2
The functional groups present in the methyl-ester oil on transmittance

Vibration type	Wave number (cm^{-1})			
	Palm oil methyl-ester	Palm oil methyl-ester (zeolite 5% & 100 °C) in 15 minutes	Palm oil methyl-ester (zeolite 5% & 100 °C) in 30 minutes	Palm oil methyl-ester (zeolite 5% & 100 °C) in 15 minutes
O-H	90.51	89.70	89.96	89.61
C-CH_3 (stretching)	13.11	12.87	12.11	11.68
C=O	10.00	10.00	10.00	10.00
CH_2 bending (C-C)	64.59	63.62	63.60	63.08
CH_3 bending (C-C)	79.65	78.57	78.73	78.19
C-O	41.98	41.45	41.29	40.95
C-C	81.66	80.66	79.88	78.07
C-C (C out plane)	89.87	88.93	89.28	88.79
C-CL	-	-	69.35	68.58
C-Br	-	-	-	90.10

Table 2 demonstrates that the methyl-ester hydrocarbon chain remains relatively long, as indicated by its dominant transmittance of 13.11% in the main forming functional group (C-CH_3). After heating with zeolite, the results decreased to 12.87%, 12.11%, and 11.68%. This indicates that the main compound forming the methyl ester is still quite long because the transmittance is still in the range of 10%-25%. Additionally, we detected other forming groups, specifically C-C, emerging from the compound bond chain with a transmittance value of 89.87%. With the addition of methyl-ester and zeolite heating time, the transmittance values decreased to 88.98%, 89.28%, and 88.79%, respectively. This decrease is an indication that there is a break in the hydrocarbon chain and a dominance of functional groups, which increases with increasing heating time [30].

Table 2 also shows the supporting functional groups, including C=O, which has a constant value of 10%. In addition, there are C-O compounds that bind to oxygen with a value of 41.98%, 41.45%, 41.29%, and 40.95%. As the heating time increases in this functional group, the transmittance value decreases, indicating an increase in the dominance of carbon and oxygen bonds in the heated methyl-ester compound. The FTIR results also showed halogen compounds trapped in the methyl-ester functional groups, namely C-CL and C-Br. This group has transmittance at 69.35%, 68.58% for C-CL, and 90.10% for C-Br. In this scenario, the zeolite transports the halogen compounds, combining with the methyl ester to function as the catalyst. The FTIR test finally detects this trapped compound, which stabilizes as heating increases.

3.2 Analysis of Viscosity, Flash Point, and Calorific Value

Figure 3 shows the effect of catalytic cracking on the properties (viscosity, flash point, and calorific value) change of methyl ester. Figure 3(a) shows the viscosity of the biodiesel methyl ester after the cracking process for 0 to 30 minutes. We obtained the graph by testing the viscosity with a viscometer using the ASTM D88 standard. The test results for the values on the graph revealed that the long heating time of the methyl-ester with a 5% zeolite mixture was the cause of the trend. The graph

shows a trend where there is a decrease in the viscosity value for each heating time of methyl-ester with a 5% zeolite mixture, but there is a not-too-significant increase at 30 minutes of heating time.

The viscosity of the biodiesel before cracking was 5.12436 cSt. Subsequently, the cracking process for 10 minutes decreased to 4.53232 cSt. The heating time further decreased to 3.93219 cSt, 3.27897 cSt, and 3.21680 cSt for 15 minutes, 20 minutes, and 25 minutes. At 30 minutes of heating time, it has a value of 3.25827 cSt. The fuel parameter, viscosity, determines the ease of injecting and atomizing the fuel in the combustion chamber. Figure 3(a) demonstrates that the viscosity value decreases as the heating time of the 5% methyl-ester and zeolite mixture increases. The reason for this is that the chain of hydrocarbon compounds that initially attracted each other in the methyl ester began to stretch, break, and eventually cut off. Due to this, the intermolecular forces are getting weaker, and the viscosity value is decreasing. The FTIR results demonstrate this, revealing a transmittance of 89.87%–88.79% in the absorption of waves 850.02-847.52 cm^{1}. In this absorption area, there is a single hydrocarbon chain (C-C) cut off from the main hydrocarbon chain, whose concentration is increasing. This value indicates a significant number of broken single chains within the long compound chain. This phenomenon leads to a proven decrease in viscosity [31].

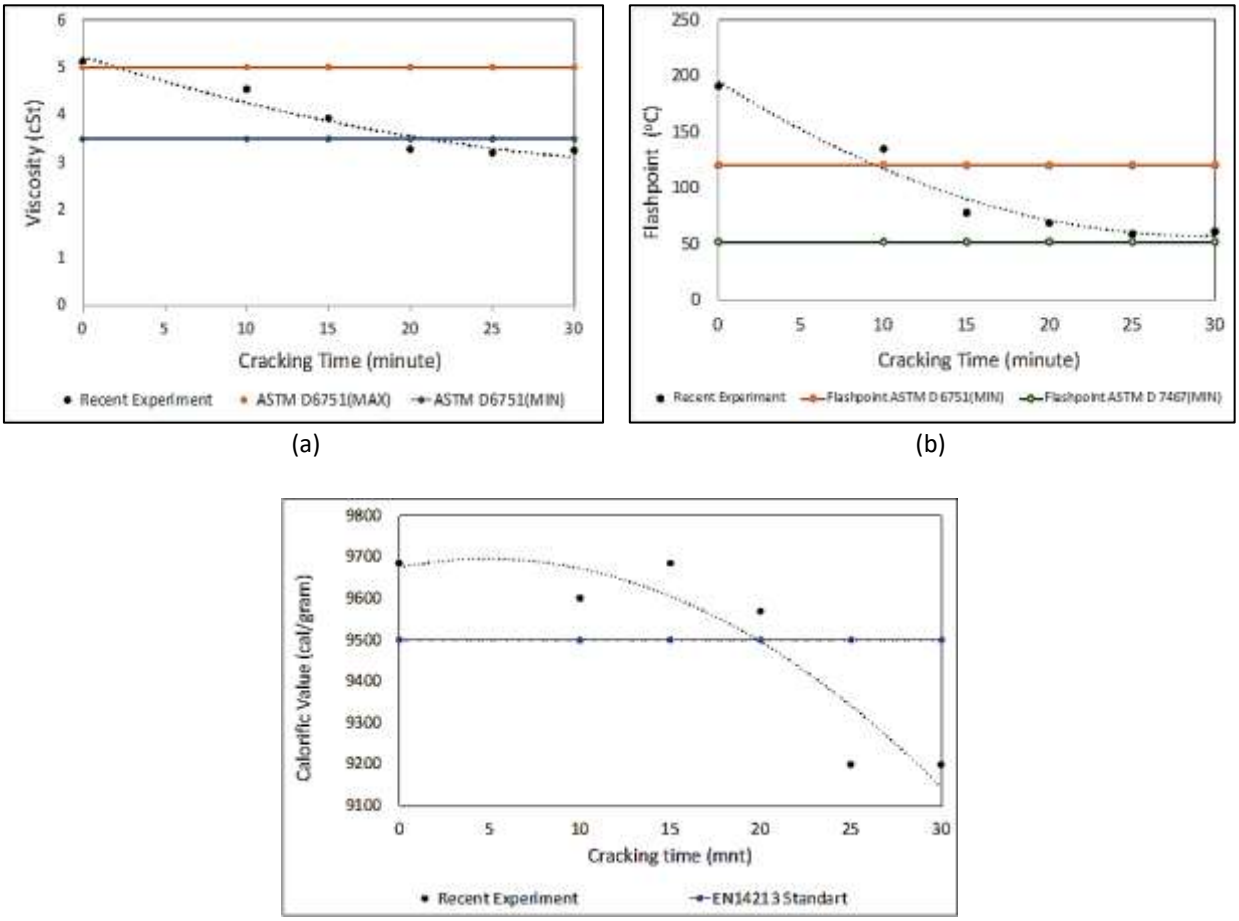

Fig. 3. Effect catalytic cracking on (a) Viscosity (b) Flashpoint of biodiesel (c) Calorific value

Figure 3(a) also shows that, after heating for 10 minutes, the methyl-ester still does not meet the ASTM D7467 standards because it exceeds its maximum value. After 15-20 minutes of heating, the methyl ester still meets the minimum and maximum standards of ASTM D6751 and ASTM D7467. Furthermore, after heating for 25-30 minutes, the methyl-ester still meets the minimum standards of ASTM D7467 but does not meet the ASTM D6751 standards because it does not reach its minimum

value. Figure 3(b) displays the biodiesel's flash point. We discovered that the trend emerged from the duration of heating the methyl-ester with a 5% zeolite mixture until it reached the flash point value. The graph shows that as the heating time goes up, the flash point value of the methyl ester in a 5% zeolite mixture goes down. The result was 191°C at a heating time of 0 minutes, 135°C at 10 minutes, and 69°C, 59°C, and 61°C at 15 minutes to 30 minutes. The flash point is the minimum temperature at which the fuel can cause sparks, such as a flash. In addition, the flash point will indicate the level of volatility of the fuel. The analysis reveals that the fatty acid content has led to a decrease in the flashpoint test graph. Fatty acids will affect the flash point because the structure of fatty acids is in the form of a straight chain, which makes the surface area of the molecule larger. As a result, fatty acids have quite large intermolecular forces compared to conventional petroleum fuel compositions.

The graph in Figure 3(b) shows a decrease in the flashpoint value as a result of catalytic cracking. The shorter hydrocarbon chains and longer heating time of the methyl-ester with a 5% zeolite mixture are responsible for this. The FTIR results demonstrate this, showing a decrease in wave absorption from 850.02 cm^{-1} to 847.52 cm^{-1}. In this absorption area, there is a chain of single hydrocarbon groups (C-C), which indicates that there is a broken chain in the long compound chain. This will lead to a decrease in the value of the intermolecular forces as they become increasingly stretched. The small intermolecular forces make it easier for the hydrocarbon bonds to break the chain and make the evaporation value smaller. The observation results also indicate that the flash point value of methyl-ester meets the minimum standard values of ASTM D6751 and ASTM D7467. However, after heating for 15-30 minutes, it only meets the minimum limits of ASTM D7467.

Figure 3(c) displays a graph of the changes in the calorific value of the methyl ester due to catalytic cracking for 0-30 minutes. We tested the calorific value of the methyl ester using a bomb calorimeter. The results indicate that heating the methyl ester for an extended period with a 5% zeolite mixture alters the calorific value. The graph demonstrates a decrease in the calorific value of methyl ester upon cracking using natural zeolite. At a heating time of 0 minutes, the calorific value was 9683.924. It increased significantly in 25-30 minutes, with values of 9198.8928 cal/gr and 9198.9928 cal/gr. Constituent compounds, which rely on the basic constituents, affect the heating value of biodiesel. Increasing the heating time and catalyst concentration in the catalytic-cracking process speeds up the reaction and increases the number of molecular collisions, leading to the breaking of more and more carbon chains.

Furthermore, the termination of this carbon chain affects the molecular weight, which will get smaller and cause the heating value to decrease. The FTIR results support this, showing transmittance of 89.87%-88.79% for the absorption of waves 850.02-847.52 cm^{1}. In this absorption area, there is a single hydrocarbon chain (C-C) cut off from the main hydrocarbon chain, whose concentration is increasing. This value confirms that the length of the broken chain in the compound chain has increased. This phenomenon verifies a decrease in the heating value. The formation of C-Br and C-Cl bonds upon heating for 25-30 minutes further supports this phenomenon. This bond has a lower breaking energy than C-C, and because of this, the heating value decreases. Figure 3(c) shows that after cracking for 0-20 minutes, the methyl ester still met the minimum standards. However, after cracking for 25-30, it does not reach the minimum limit of the EN14213 standard.

4. Conclusions

The impact of catalytic cracking with natural zeolite on the methyl ester's characteristics has been observed. The study's findings led to the following conclusions:

i. The FTIR test revealed that the hydrocarbon compounds separated from the long compounds at the absorption of waves 850.02–847.52 cm^1, with a transmittance of 89.87% to 88.79%. This absorption area indicates that there is a single hydrocarbon chain (C-C) cut off from the main hydrocarbon chain whose concentration and dominance are increasing.

ii. Catalytic cracking using a 5% natural zeolite decreased some of the methyl ester's physical properties (viscosity, flashpoint, and calorific value). The chain of hydrocarbon compounds is stretched and broken into shorter hydrocarbons. It causes the intermolecular forces to weaken, leading to a decrease in the viscosity, flashpoint, and calorific value of methyl ester. The FTIR results support this, showing transmittance of 89.87%–88.79% for the absorption of waves 850.02-847.52 cm^1. In this absorption area, there is a single hydrocarbon chain (C-C) cut off from the main hydrocarbon chain, whose concentration is increasing. This value confirms that the length of the broken chain in the compound chain has increased.

Acknowledgement
This research was funded by a grant from Hibah Guru Besar, Universitas Brawijaya, Malang, Indonesia. (Kontrak Penelitian Nomor: 10/UN10.F07/H.PN/2023).

References

[1] Kong, Yu Man, Joon Hin Lee, Kiat Moon Lee, and Wah Yen Tey. "Techniques of improving microalgae in biomass clean energy: A short review." *Progress in Energy and Environment* (2019): 6-20.

[2] Osman, Shahrul Azmir, Mas Fawzi, and Siti Hajar Saimi. "A review of comparative characteristic study on effect of biodiesel B20 on Compression Ignition (CI) engine performances and exhaust emissions." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 62, no. 2 (2019): 221-234.

[3] Alimin, Ahmad Jais, and Olawale Kazeem Babalola. "A review on the influence of additive blended biodiesel to the performance and emission characteristics of heavy-duty diesel engines." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 111, no. 1 (2023): 180-193. https://doi.org/10.37934/arfmts.111.1.180193

[4] Rodrigues Jr, Jorge de A., Fabianne de P. Cardoso, Elizabeth R. Lachter, Luciana RM Estevão, Edson Lima, and Regina SV Nascimento. "Correlating chemical structure and physical properties of vegetable oil esters." *Journal of the American Oil Chemists' Society* 83, no. 4 (2006): 353-357. https://doi.org/10.1007/s11746-006-1212-0

[5] Nursal, Ridwan Saputra, Zakiman Zali, Shahril Jalil, Amir Khalid, and S. A. Hadi. "Experimental study of the bio-additives effects in biodiesel fuel on performance, emissions and combustions characteristics of diesel engine." *ARPN Journal of Engineering Applied Sciences* 12, no. 6 (2017): 1997-2005.

[6] Wedel, Randall Von. *Technical handbook for marine biodiesel: In rescreational boats*. Cyto Culture Environmental Biotechnology, CytoCulture International Inc., California, 1999.

[7] Köten, Hasan, and Abdullah Selim Parlakyiğit. "Effects of the diesel engine parameters on the ignition delay." *Fuel* 216 (2018): 23-28. https://doi.org/10.1016/j.fuel.2017.11.136

[8] Noor, CW Mohd, M. M. Noor, and R. Mamat. "Biodiesel as alternative fuel for marine diesel engine applications: A review." *Renewable and Sustainable Energy Reviews* 94 (2018): 127-142. https://doi.org/10.1016/j.rser.2018.05.031

[9] Ibadurrohman, Ibrahim Ahmad, Nurkholis Hamidi, Lilis Yuliati, and Benedict Amadeus Valentino. "Experimental investigation on the effect of carbon chain length to the droplet combustion characteristic of fatty acid methyl ester." In *IOP Conference Series: Materials Science and Engineering*, vol. 1034, no. 1, p. 012060. IOP Publishing, 2021. https://doi.org/10.1088/1757-899X/1034/1/012060

[10] Nasreen, Sadia, Muhammad Nafees, Liaqat Ali Qureshi, Muhammad Shahbaz Asad, Ali Sadiq, and Syed Danial Ali. "Review of catalytic transesterification methods for biodiesel production." *Biofuels: State of development* 6 (2018): 93-119. https://doi.org/10.5772/intechopen.75534

[11] Barnwal, B. K., and M. P. Sharma. "Prospects of biodiesel production from vegetable oils in India." *Renewable and Sustainable Energy Reviews* 9, no. 4 (2005): 363-378. https://doi.org/10.1016/j.rser.2004.05.007

[12] Hamidi, Nurkholis, Ibrahim Ahmad Ibadurrohman, Lilis Yuliati, Winarto Winarto, and Djarot B. Darmadi. "The effect of alcohol compounds on droplet combustion characteristics of unsaturated fatty acid of linoleic acid." *Trends in Sciences* 20, no. 7 (2023): 6720-6720. https://doi.org/10.48048/tis.2023.6720

[13] Hamidi, Nurkholis, Widya Wijayanti, and Rizal Fahmi. "Ignition and combustion characteristics of a single droplet of blended fuels of Kemiri Sunan [reutealis trisperma (blanco) airy shaw] biodiesel." In *Current Approaches in Engineering Research and Technology* 1 (2024): 79-92. https://doi.org/10.9734/bpi/caert/v1/8005E
[14] Lin, Ronghong, Yiying Zhu, and Lawrence L. Tavlarides. "Mechanism and kinetics of thermal decomposition of biodiesel fuel." *Fuel* 106 (2013): 593-604. https://doi.org/10.1016/j.fuel.2012.12.013
[15] Tamunaidu, Pramila, and Subhash Bhatia. "Catalytic cracking of palm oil for the production of biofuels: Optimization studies." *Bioresource Technology* 98, no. 18 (2007): 3593-3601. https://doi.org/10.1016/j.biortech.2006.11.028
[16] Li, Lu, Kejing Quan, Junming Xu, Fusheng Liu, Shiwei Liu, Shitao Yu, Congxia Xie, Baoquan Zhang, and Xiaoping Ge. "Liquid hydrocarbon fuels from catalytic cracking of rubber seed oil using USY as catalyst." *Fuel* 123 (2014): 189-193.
[17] Sang, Ooi Yean. "Biofuel production from catalytic cracking of palm oil." *Energy Sources* 25, no. 9 (2003): 859-869. https://doi.org/10.1080/00908310390221309
[18] Luo, Yan, Irshad Ahmed, Alena Kubátová, Jana Šťávová, Ted Aulich, S. M. Sadrameli, and W. S. Seames. "The thermal cracking of soybean/canola oils and their methyl esters." *Fuel Processing Technology* 91, no. 6 (2010): 613-617. https://doi.org/10.1016/j.fuproc.2010.01.007
[19] Abdulkareem, Ali Nasr, and Nurul Fitriah Nasir. "Biodiesel production from canola oil using TiO_2CaO as a heterogenous catalyst." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 93, no. 2 (2022): 125-137. https://doi.org/10.37934/arfmts.93.2.125137
[20] Chester, Arthur W., and Eric G. Derouane. *Zeolite characterization and catalysis*. 360. New York: Springer, 2009. https://doi.org/10.1007/978-1-4020-9678-5
[21] Nazarudin, N. "Catalytic cracking of plastic waste using nanoporous materials." PhD diss., UCL (University College London), 2012.
[22] Bhatia, Subhash. *Zeolite catalysts: principles and applications*. CRC press, 2020. https://doi.org/10.1201/9781003068389
[23] Chew, Thiam Leng, and Subhash Bhatia. "Catalytic processes towards the production of biofuels in a palm oil and oil palm biomass-based biorefinery." *Bioresource Technology* 99, no. 17 (2008): 7911-7922. https://doi.org/10.1016/j.biortech.2008.03.009
[24] Yuliansyah, Fisal, Nurkholis Hamidi, and Mega Nur Sasongko. "Pyrolysis of corn cob biomass toward gaseous products on small capacity reactor." *International Journal of Mechanical Engineering Technologies and Applications* 5, no. 1 (2024): 87-95. https://doi.org/10.21776/MECHTA.2024.005.01.9
[25] Hartmann, Martin, and Larry Kevan. "Substitution of transition metal ions into aluminophosphates and silicoaluminophosphates: characterization and relation to catalysis." *Research on Chemical Intermediates* 28, no. 7 (2002): 625-695. https://doi.org/10.1163/15685670260469357
[26] Barbosa, Antusia Santos, Antonielly Santos Barbosa, Meiry Glaúcia Freire Rodrigues, and J. M. Grau. "Preparation and Characterization: The Effect of Incorporation by Ion Exchange of Pt, Ni and Ru on a H-ZSM5 Zeolite." In *Materials Science Forum* 727, p. 32-37. Trans Tech Publications Ltd, 2012. https://doi.org/10.4028/www.scientific.net/MSF.727-728.32
[27] Wang, Ping, Baojian Shen, Dongdong Shen, Tong Peng, and Jinsen Gao. "Synthesis of ZSM-5 zeolite from expanded perlite/kaolin and its catalytic performance for FCC naphtha aromatization." *Catalysis Communications* 8, no. 10 (2007): 1452-1456. https://doi.org/10.1016/j.catcom.2006.12.018
[28] Ates, Ayten, and Christopher Hardacre. "The effect of various treatment conditions on natural zeolites: Ion exchange, acidic, thermal and steam treatments." *Journal of Colloid and Interface Science* 372, no. 1 (2012): 130-140. https://doi.org/10.1016/j.jcis.2012.01.017
[29] Anam, Khairul, Anindito Purnowidodo, Bonang Ananta, and Pavan Kumar Asur Vijaya Kumar. "The effect of load steps and initial crack length on stress distribution of fiber metal laminates." *Mechanics Exploration and Material Innovation* 1, no. 2 (2024): 54-60. https://doi.org/10.21776/ub.memi.2024.001.02.3
[30] Zakaria, Hanis, Amir Khalid, Mohamad Farid Sies, and Norrizal Mustaffa. "Overview effect of biodiesel storage on properties and characteristics." *Applied Mechanics and Materials* 465 (2014): 260-264. https://doi.org/10.4028/www.scientific.net/AMM.465-466.260
[31] Ragland, Kenneth W., Kenneth M. Bryden, and Song-Charng Kong. *Combustion Engineering*. Boca Raton, FL: CRC press, 2011. https://doi.org/10.1201/b11548